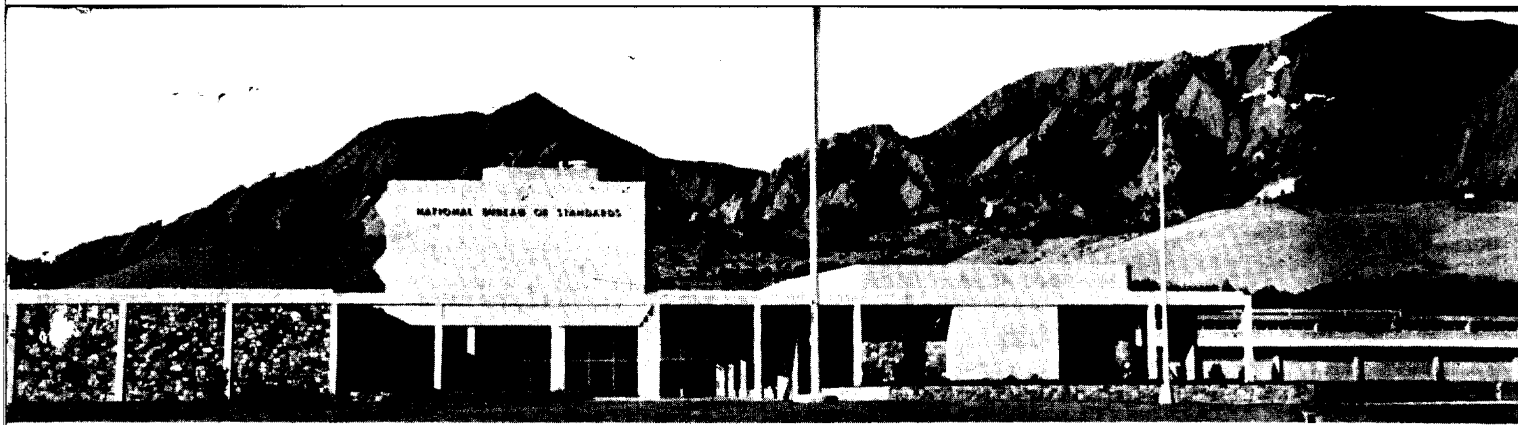

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THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS FROM 4 TO 300 K: II. OSRM IRON-1265

J. G. Hust and L. L. Sparks

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THERMAL CONDUCTIVITY STANDARD REFERENCE MATERIALS FROM 4 TO 300K: II. OSRM IRON-1265

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ABSTRACT

Thermal conductivity, electrical resistivity, Lorenz ratio, and thermopower data are reported for a specimen of OSRM iron-1265 for temperatures from 4 to 300 K. Variability of this iron was studied by means of electrical residual resistivity ratio measurements on 63 specimens. This study showed that with a two-hour anneal at 1000°C one can expect a thermal conductivity standard reference material which has variability of less than 1% in thermal conductivity.

KEY WORDS

Cryogenics, electrical resistivity, iron, Lorenz ratio, Seebeck effect, thermal conductivity, transport properties.

---

* This work was carried out at the National Bureau of Standards under the sponsorship of the NASA-Space Nuclear Propulsion Office, Cleveland.

1. Introduction

Design and development engineers in the aerospace industry continue to have urgent need for thermal and mechanical property data for new materials. For most materials, especially new or uncommon alloys, measured values of thermal conductivity are not available and predictions cannot be made with adequate confidence. To help satisfy these needs, we have constructed an apparatus for the simultaneous measurement of thermal conductivity, electrical resistivity and thermopower. Measurements have been conducted on several aerospace alloys, Hust, et al.[1] Another phase of this program, to establish standard reference data on several standard reference materials has begun. We intend to measure several specimens of materials which appear to be useful as standards. For some materials, material variability may be so great that only standard specimens (not standard materials) will be useful. Standard reference specimens or materials are useful for intercomparison of existing apparatus, for debugging new apparatus, and for calibration of comparative apparatus. The apparent large differences between the results of various investigators for a given material (50% is not unheard of) is evidence of the need for intercomparisons, calibrations, and standardization. The availability of standard reference materials will result in more accurate and more permanent transport property data for technically important solids.

This paper contains the results of our measurements on the transport properties of an iron supplied by the National Bureau of Standards, Office of Standard Reference Materials (OSRM). This iron is designated as OSRM iron-1265. OSRM iron-1265 was investigated

primarily to find a material similar to Armco iron* but less variable.

2. Apparatus and Data Analysis

The apparatus is based on the axial one-dimensional heat flow method. The specimen is a cylindrical rod 3.6 mm in diameter and 23 cm long with an electric heater at one end and a temperature controlled sink at the other. The specimen is surrounded by glass fiber and a temperature controlled shield. Eight thermocouples are mounted at equally spaced points along the length of the specimen to determine temperature gradients in the range 4 to 300 K.

The experimental data are represented by arbitrary functions over the entire range and smooth tables are generated from these functions. The number of terms used to represent each of the data sets is optimized, through the use of orthonormal functions, so that none of the precision of the data is lost by underfitting nor are any unnecessary oscillations introduced by overfitting. A detailed description of this apparatus and the methods of data analysis is given by Hust, et al.[1]

3. Specimen Characterization

Density as measured by air and water weighings is 7.867 g/cm^3 Rockwell hardness and grain size are B23.5 and 0.0507 mm respectively. Each of these values is for the material in the annealed state as described in the following discussion. The composition of OSRM iron-1265 is as follows:

---

* The use in this paper of trade names of specific products is essential to a proper understanding of the work presented. Their use in no way implies any approval, endorsement, or recommendation by NBS. Armco iron is a registered trade name of a commercially pure iron produced by Armco Steel Corporation.

Element	%	Element	ppm
C	.010	B	1.5
Mn	.008	Pb	.3
P	.002	Zr	.4
S	.008	Sb	.5
Si	.013	Bi	.1
Cu	.006	Ag	.02
Ni	.037	Ca	.4
Cr	.007	Mg	<.2
V	.0005	Se	<.02
Mo	.005	Te	<.05
W	.00005	Zn	2
Co	.007	O_2	60
Ti	.004	N_2	10
As	.003	Ge	10
Sn	.0002		
Al	.002	H_2	~ 1
Nb	<.0001	Ce	.02
Ta	<.001	La	.01
		Pr	<.01

An extensive resistivity variability study was conducted on OSRM iron-1265, the object being to determine if it could be heat treated in such manner that the thermal conductivity would be the same for each specimen. This was achieved with a 2-hour, 1000°C anneal in either a vacuum or helium atmosphere. The results of this study are shown as residual resistivity ratios in table 1. The ratio given is resistivity at 273.15 K to resistivity at 4 K. Specimens labeled C2T, A6L, C5L, AlL, and A5T were obtained from 1/4" diameter rods; the remaining specimens were machined from 1-1/4" rods. Based on the 63 residual resistivity ratio measurements made on these specimens in various stages of heat treatment, the following is concluded: The large 1-1/4" diameter specimens are significantly different in residual resistivity

ratio from the smaller 1/4" diameter specimens in the as received condition. The ratio of the small rods is 22.01 ± 0.20 while the ratio of the larger rods is 19.52 ± 0.44.

Various heat treatments were tried to remove the differences in ratio of the two sets of rods. After 500°C for 1 hour the ratios increased but were still different (small rods = 23.53 ± 0.20; large rods = 22.14 ± 0.34). Raising the temperature to 1000°C for 2 hours produced rods which are indistinguishable, (small rods = 23.39 ± 0.28; large rods = 23.29 ± 0.20; all rods = 23.33 ± 0.24). The variation shown is 2s, where s is the estimated standard deviation, and includes material and measurement variability. In order to study the possibility of a change in these ratios with age, one set of rods was measured after about 50 days from the 1000°C treatment; no significant change was detected (ratio = 23.40 ± 0.20). It was also believed that aging could be simulated by heating to 400°C for $2\frac{1}{2}$ days; however, this changed the ratio to 24.94 ± 0.26 with no difference between the large and small rods. This change cannot be explained at the present time.

These measurements show that OSRM iron-1265 can be used as a thermal conductivity standard below room temperature with a variability of about 1% if annealed at 1000°C for 2 hours. We plan to measure some of these specimens from time to time during the next year to determine the effect of long term aging, i.e., more than 50 days.

4. Results

The transport properties of OSRM iron-1265, specimen A5T, were measured in the thermal conductivity apparatus. These data are presented in tables 2 and 3.

The experimental data were functionally represented with the following equations:

$$\ell n\lambda = \sum_{i=1}^{n} a_i [\ell nT]^{i+1} \tag{1}$$

$$\rho = \sum_{i=1}^{m} b_i [\ell nT]^{i-1} \tag{2}$$

$$S = \sum_{i=1}^{\ell} c_i [\ell nT']^{i}/T'; \qquad T' = \frac{T}{10} + 1 \tag{3}$$

where λ = thermal conductivity, ρ = electrical resistivity, S = thermopower, and T = temperature. Temperatures are based on the IPTS-68 scale above 20 K and the NBS P2-20 (1965) scale below 20 K. The parameters, a_i, b_i, and c_i, determined by least squares, are presented in table 4. Further details of this procedure are described by Hust, et al.[1] The deviations of the experimental data from these equations are given in tables 5 through 7 and in figures 1 through 3. The horizontal bars in figures 2 and 3 indicate the temperature span across the specimen for each run. The "observed" thermal conductivities are computed from the mean temperature gradients indicated by adjacent thermocouples. Calculated values of λ, ρ, S, and L = $\rho\lambda/T$ (Lorenz ratio) are presented in table 8 and in figures 4 through 7.

A detailed error analysis for this system has been presented previously by Hust, et al.[1] Based on this analysis of systematic and random errors the uncertainty estimates (with 95% confidence) are as follows:

thermal conductivity:	2.5% at 300 K, decreasing as T^4 to 0.70% at 200 K, 0.70% from 200 K to 50 K, increasing inversely with temperature to 1.5% at 4 K.
electrical resistivity:	0.25%
thermopower:	0.5% + 0.2 μV/K at 4 K, 0.2% + 0.05 μV/K at 30 K, and 0.1% + 0.03 μV/K above 76 K.

The thermopower values given here are absolute values although our measurements were carried out with respect to normal silver wire. The absolute thermopowers of normal silver reported by Borelius, et al. [3] were used to convert the experimental data to the absolute scale.

5. Discussion

This iron is purer than the Armco iron previously measured. [2] The residual resistance ratio is near 23 compared to 13 for Armco iron. Also the Lorenz ratio shows a more pronounced dip at 65 K as is expected for a more pure material. A preliminary examination of the intrinsic resistivity, ρ_i, computed from Mathiessen's rule reveals a dependence of ρ_i on ρ_o. An attempt will be made in the future to correlate both the Lorenz ratios and apparent intrinsic resistivity changes with the residual resistivity.

6. Acknowledgments

We wish to thank R. E. Michaelis of NBS, OSRM for supplying these specimens along with helpful discussions. This measurement program has been carried out under the helpful guidance of R. L. Powell.

7. References

1. J. G. Hust, R. L. Powell, and D. H. Weitzel, "Thermal Conductivity, Electrical Resistivity, and Thermopower of Aerospace Alloys from 4 to 300 K," NBS Report 9732 (1969).
2. J. G. Hust, "Thermal Conductivity Standard Reference Materials from 4 to 300 K. I. Armco Iron," NBS Report 9740 (1969).
3. G. Borelius, W. H. Keesom, C. H. Johansson, and J. O. Linde, "Establishment of an Absolute Scale for the Thermoelectric Force," Proc. Kon, Akad. Amsterdam 35, 10 (1932).

Notes Relating to Tables

Table 2

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not clearly labelled. The following is a line by line explanation of this table:

1st line -	Data identification.
2nd line -	Thermocouple emfs (μV).
3rd line -	Seebeck emf (μV), specimen current (mA), specimen voltage drop (μV).
4th line -	Sample heater voltage (μV), current (mA), platinum resistance thermometer voltage (μV), platinum resistance thermometer current (mA), cryogenic bath pressure (mm of Hg), room temperature (°C), code indicating type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water).
5th line -	Thermocouple temperatures (K).
6th line -	Heater power (W), reference temperature (K), specimen resistance (Ω).

Table 3

The data listed are, in part, card images of experimental data as read into the computer for data processing. These data are not labelled clearly. The following is a line by line explanation of this table:

1st line - Data identification.

2nd line - Platinum resistance thermometer voltage (μV), cryogenic bath pressure (mm of Hg), room temperature (°C), platinum resistance thermometer current (mA), code indicating type of cryogenic bath (1 = liquid helium, 2 = liquid hydrogen, 3 = liquid nitrogen, 4 = dry ice-alcohol, 5 = ice-water), specimen current (mA), specimen voltage (μV), mean emf of eight thermocouples (μV).

3rd line - Reference temperature (K), specimen resistance (Ω), specimen temperature (K).

Tables 5, 6, and 7

These data are semi-processed computer output. Temperature is in Kelvin, thermal conductivity is in $Wm^{-1} K^{-1}$, electrical resistance is in ohms, and thermovoltage is in μV.

Table 1. Residual resistivity ratio ($\rho_{273\,K}/\rho_{4\,K}$) of OSRM iron-1265

Specimen	Ratio					
	As received	500°C 1 hr	500°C 8 hr	1000°C 2 hr	400°C $2\frac{1}{2}$ days	Aging 50 days
C2T	21.97(a)	23.53	24.12	23.31(e)	24.84	25.00
A6L	22.16	-----	-----	23.22(f)	24.85	24.97
C5L	21.94	-----	-----	23.40(f)	-----	23.47
A1L	22.04	-----	-----	23.59(c)	-----	23.52
A5T	22.03(b)	-----	-----	23.42(f)	-----	23.42
2A-1-1	19.35	21.96	22.32	23.47(e)	25.12	25.24
2A-1-2	19.50	-----	-----	23.31(c)	-----	23.35
2A-1-3	19.30	-----	-----	-----	-----	-----
2A-1-4	19.38	-----	-----	23.27(f)	-----	-----
2A-3-1	19.77	21.83	22.25	23.20(e)	24.94	25.01
2A-3-2	19.92	-----	-----	23.20(c)	-----	23.25(d)
2A-3-3	19.73	-----	-----	-----	-----	-----
2A-3-4	19.93	-----	-----	-----	-----	-----
2C-1-1	19.42	21.70	22.00	23.23(e)	-----	23.44
2C-1-2	19.12	-----	-----	23.41(c)	-----	23.40
2C-1-3	19.46	-----	-----	-----	-----	-----
2C-1-4	19.56	-----	-----	-----	-----	-----
2C-3-1	19.34	21.93	21.99	23.27(e)	-----	23.40
2C-3-2	19.49	-----	-----	-----	-----	-----
2C-3-3	19.57	-----	-----	-----	-----	-----
2C-3-4	19.40	-----	-----	-----	-----	-----

(a) repeat measurement = 21.91

(b) ratio of A5T thermal conductivity specimen = 21.89

(c) these were heat treated in vacuum, the remaining were heated to 1000°C in a helium atmosphere (1 atm pressure).

(d) repeat measurements = 23.39, 23.31

(e, f) these were done in separate heat treatments to detect reproducibility of heat treatment

Table 2. Basic semi-processed temperature gradient data for OSRM iron-1265

```
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28,70 950 8
   13.69     17.67     21.65     25.64     29.07     32.79     36.42     39.70
    -0.08    200.00     13.00
   693129    6.1500    -0.00      -0.0     636.3      21.2       1.0
THERMOCOUPLE TEMPERATURES
   5.000     5.313     5.601     5.880     6.141     6.397     6.639     6.880
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.2627-003             4.027               6.4980-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28,70  1045  9
   28.95     37.86     46.15     54.32     61.65     69.04     76.26     82.85
    -0.07    200.00     13.02
  1104174    9.8000    -0.00      -0.0     636.2      21.6       1.0
THERMOCOUPLE TEMPERATURES
   6.112     6.747     7.306     7.841     8.334     8.804     9.253     9.681
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.0821-002             4.027               6.5080-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28,70 1233 10
   60.76     78.59     94.86    110.23    124.13    137.70    150.77    162.90
    -0.00    200.00     13.06
  1746102   15.5000    -0.00      -0.0     636.4      22.0       1.0
THERMOCOUPLE TEMPERATURES
   8.258     9.409    10.417    11.347    12.196    13.000    13.764    14.491
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.7065-002             4.027               6.5290-005
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28,70 1345 11
  125.22    159.45    189.72    217.82    243.03    267.20    290.26    311.88
     1.14    200.00     13.20
  2836895   25.1800    -0.00      -0.0     636.4      22.0       1.0
THERMOCOUPLE TEMPERATURES
  12.245    14.283    16.049    17.674    19.150    20.548    21.880    23.154
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 7.1435-002             4.027               6.6010-005
------------------------------------------------------------
```

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1 1449 13
   19.62    27.96    36.43    44.82    52.56    60.50    68.49    76.00
     0.77    200.00    13.34
  1726114   15.3200   219.73       2.0      650.4      22.0       2.0
THERMOCOUPLE TEMPERATURES
  20.943   21.439   21.929   22.411   22.873   23.334   23.793   24.245
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.6444-002              19.827                6.6710-005
----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1,70 1626 14
   39.72    56.85    73.70    90.16   105.46   120.81   136.06   150.63
     2.68    200.00    13.50
  2528066   22.4400   220.10       2.0      650.0      22.1       2.0
THERMOCOUPLE TEMPERATURES
  22.122   23.132   24.113   25.071   25.980   26.880   27.772   28.646
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 5.6748-002              19.837                6.7490-005
----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1032 15
   83.34   117.70   150.73   182.64   212.69   242.59   272.40   301.47
    12.16    200.00    14.02
  3758734   33.3400   224.46       2.0      648.6      21.7       2.0
THERMOCOUPLE TEMPERATURES
  24.789   26.819   28.766   30.652   32.453   34.236   36.014   37.771
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.2532-001              19.956                7.0110-005
----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 16
  148.37   208.24   266.01   322.71   378.23   434.69   493.12   552.71
    52.77    200.00    15.67
  5220315   46.2700   227.48       2.0      649.0      22.2       2.0
THERMOCOUPLE TEMPERATURES
  28.700   32.269   35.720   39.116   42.458   45.825   49.279   52.793
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 2.4154-001              20.037                7.8325-005
----------------------------------------------------------------
```

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1509 17
 250.48   352.85   456.98   566.07   683.03   809.79   949.81  1102.32
  262.39   200.00    22.62
 7055324   62.4600   232.28       2.0      648.2      23.0       2.0
THERMOCOUPLE TEMPERATURES
 34.913   41.067   47.276   53.688   60.463   67.656   75.447   83.791
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.4068-001              20.164              1.1310-004
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1620 18
 250.50   352.90   456.94   565.92   682.97   809.69   949.83  1102.32
  262.37   200.00    22.62
 7055354   62.4600   232.19       2.0      648.9      23.0       2.0
THERMOCOUPLE TEMPERATURES
 34.911   41.068   47.271   53.677   60.458   67.648   75.446   83.789
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.4068-001              20.162              1.1310-004
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25,70 1403 2
  26.82    43.14    59.69    76.35    93.17   110.13   127.26   144.61
   58.70    150.00    27.17
 2326217   20.6000   9287.54      2.0      635.4      21.9       3.0
THERMOCOUPLE TEMPERATURES
 77.419   78.315   79.221   80.129   81.046   81.967   82.899   83.837
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 4.7920-002              75.949              1.8113-004
------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25,70 1736 3
  46.76    79.53   113.08   147.13   181.82   217.02   253.02   289.64
  128.77    150.00    30.14
 3267955   28.9300   9298.25      2.0      635.6      22.6       3.0
THERMOCOUPLE TEMPERATURES
 78.561   80.353   82.178   84.022   85.895   87.785   89.715   91.666
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 9.4542-002              75.998              2.0093-004
------------------------------------------------------------
```

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 918 4
   96.02   162.83   232.40   304.07   378.19   454.24   533.07   613.92
   305.82    150.00     37.39
  4578467   40.5000   9326.50         2.0      633.5       21.0       3.0
THERMOCOUPLE TEMPERATURES
  81.377  84.998  88.737  92.557  96.478 100.468 104.576 108.755
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.8543-001            76.127                2.4929-004
------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 1310 5
  172.59   299.68   435.11   577.24   726.56   881.50  1043.58  1210.93
   688.22    150.00     51.70
  6143712  54.2900   9364.48         2.0      635.8       22.2       3.0
THERMOCOUPLE TEMPERATURES
  85.633  92.492  99.634 107.025 114.690 122.544 130.669 138.961
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.3354-001            76.300                3.4465-004
------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 1655 6
  330.28   586.70   867.84  1168.22  1487.29  1820.98  2171.69  2535.71
  1594.28    150.00     85.71
  8329310  73.4400   9416.20         2.0      636.4       22.9       3.0
THERMOCOUPLE TEMPERATURES
  94.341 107.735 122.073 137.065 152.681 168.720 185.318 202.309
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 6.1170-001            76.535                5.7139-004
------------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 3 1600 19
   66.76   123.84   181.70   239.60   297.90   356.29   415.41   474.74
   299.87    150.00    148.08
  3296055  29.0500  34417.35         2.0      631.8       22.1       4.0
THERMOCOUPLE TEMPERATURES
 195.865 198.523 201.211 203.897 206.596 209.294 212.020 214.752
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 9.5750-002           192.750                9.8723-004
------------------------------------------------------------------
```

Table 2 (continued)

```
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4 1027 20
  137.08   254.58   373.98   494.34   616.16   798.78   863.54   989.30
   613.14    150.00    163.55
  4709392  41.4500  34445.90       2.0     631.6      21.0       4.0
THERMOCOUPLE TEMPERATURES
 199.275  204.717  210.245  215.788  221.378  226.906  232.674  238.391
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 1.9520-001            192.887                1.0903-003
-----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4,70 1600 21
  245.61   470.82   702.44   937.44  1177.17  1420.17  1669.09  1921.62
  1148.37    150.00    191.69
  6485870  57.0400  34523.00       2.0     630.6      22.1       4.0
THERMOCOUPLE TEMPERATURES
 204.678  215.070  225.687  236.395  247.262  258.222  269.403  280.710
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 3.6995-001            193.256                1.2779-003
-----------------------------------------------------------------
THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 5,70 1405 22
   71.22   135.32   200.40   265.50   331.01   396.64   463.24   530.07
   281.31    100.00    164.91
  3297690  29.0000  50978.00       2.0     630.6      21.9       5.0
THERMOCOUPLE TEMPERATURES
 276.512  279.374  282.279  285.186  288.111  291.041  294.014  296.998
HEATER POWER   REFERENCE TEMPERATURE   SPECIMEN RESISTANCE
 9.5633-002            273.316                1.6491-003
-----------------------------------------------------------------
```

Thermocouple Positions	2.2202	4.7594	7.2989	9.8382
(cm from floating sink)	12.379	14.919	17.458	19.998
Specimen diameters (cm)	0.36627	0.36632	0.36619	0.36609
between thermocouples	0.36619	0.36606	0.36634	
starting from floating sink				

Table 3. Basic semi-processed isothermal electrical resistivity data for OSRM iron-1265

```
 ISOTHERMAL RESISTIVITY DATA FOR OSRM IRONMAY 28,70  915  7
  -0.00   636.40    21.50    -0.00     1.00   200.00    12.99     4.96
REFERENCE TEMPERATURE   SPECIMEN RESISTANCE   SPECIMEN TEMPERATURE
        4.027                6.4950-005               4.422
------------------------------------------------------------
  ISOTHERMAL RESISTIVITY DATA FOR OSRM IROJUNE 1,70  1319  12
  219.37   649.00    22.00     2.00     2.00   200.00    13.23     0.63
REFERENCE TEMPERATURE   SPECIMEN RESISTANCE   SPECIMEN TEMPERATURE
        19.817               6.6160-005               19.853
------------------------------------------------------------
ISOTHERMAL RESISTIVITY DATA FOR IRON OSRM MAY 25,70 1147 1
 9273.15   634.70    20.90     2.00     3.00   100.00    16.28     4.42
REFERENCE TEMPERATURE   SPECIMEN RESISTANCE   SPECIMEN TEMPERATURE
        75.884               1.6282-004               76.128
------------------------------------------------------------
```

Table 4. Parameters in equations 1, 2, and 3 for OSRM iron-1265

COEFFICIENTS FOR THERMAL CONDUCTIVITY	COEFFICIENTS FOR ELECTRICAL RESISTIVITY	COEFFICIENTS FOR THERMOPOWER
-1.48463068+001	1.52995843-005	-4.42050903+002
6.93779265+001	-6.57221842-005	2.91385157+003
-1.13470636+002	1.28083500-004	-7.88597272+003
1.01420592+002	-1.50027718-004	1.14395105+004
-5.68004853+001	1.17942860-004	-9.71586106+003
2.10770015+001	-6.57740194-005	4.92662120+003
-5.27537674+000	2.67952461-005	-1.44644001+003
8.81839451-001	-8.08115141-006	2.26661972+002
-9.43950407-002	1.80581011-006	-1.47175223+001
5.85191930-003	-2.95519976-007	
-1.59785857-004	3.44469418-008	
	-2.70952664-009	
	1.28939040-010	
	-2.80388287-012	

Table 5. Thermal conductivity deviations for OSRM iron-1265.

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 950 8

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
5.156	0.313	3.28+001	3.31+001	-0.7
5.457	0.289	3.56+001	3.52+001	1.2
5.741	0.279	3.68+001	3.71+001	-0.6
6.011	0.260	3.96+001	3.89+001	1.8
6.269	0.256	4.01+001	4.05+001	-1.0
6.518	0.242	4.25+001	4.22+001	0.8
6.759	0.241	4.26+001	4.37+001	-2.8

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 1045 9

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
6.430	0.635	4.11+001	4.16+001	-1.3
7.027	0.559	4.66+001	4.55+001	2.5
7.574	0.534	4.88+001	4.90+001	-0.4
8.087	0.493	5.30+001	5.23+001	1.3
8.569	0.470	5.55+001	5.54+001	0.1
9.028	0.449	5.81+001	5.84+001	-0.5
9.467	0.428	6.09+001	6.12+001	-0.6

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28, 70 1233 10

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
8.833	1.151	5.67+001	5.72+001	-0.8
9.913	1.008	6.47+001	6.41+001	0.9
10.882	0.930	7.02+001	7.03+001	-0.2
11.772	0.850	7.69+001	7.59+001	1.2
12.598	0.804	8.12+001	8.11+001	0.1
13.382	0.764	8.55+001	8.59+001	-0.5
14.128	0.727	8.97+001	9.04+001	-0.8

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 28,70 1345 11

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
13.264	2.038	8.45+001	8.52+001	-0.9
15.166	1.766	9.75+001	9.66+001	0.9
16.862	1.625	1.06+002	1.06+002	-0.4
18.412	1.475	1.17+002	1.15+002	1.7
19.849	1.398	1.23+002	1.22+002	0.6
21.214	1.332	1.29+002	1.29+002	0.1
22.517	1.274	1.35+002	1.35+002	-0.1

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1 1449 13

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
21.191	0.496	1.28+002	1.29+002	-0.6
21.684	0.489	1.30+002	1.31+002	-1.0
22.170	0.483	1.32+002	1.34+002	-1.3
22.642	0.462	1.38+002	1.36+002	1.6
23.104	0.460	1.39+002	1.38+002	0.4
23.563	0.459	1.39+002	1.40+002	-0.7
24.019	0.452	1.41+002	1.42+002	-0.6

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 1,70 1626 14

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
22.627	1.010	1.35+002	1.36+002	-0.3
23.623	0.981	1.39+002	1.40+002	-0.5
24.592	0.958	1.43+002	1.44+002	-0.9
25.525	0.909	1.51+002	1.48+002	1.9
26.430	0.900	1.52+002	1.51+002	0.6
27.326	0.892	1.54+002	1.54+002	-0.3
28.209	0.874	1.56+002	1.57+002	-0.2

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1032 15

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
25.804	2.030	1.49+002	1.49+002	-0.0
27.792	1.947	1.55+002	1.56+002	-0.3
29.709	1.887	1.60+002	1.61+002	-0.5
31.553	1.801	1.68+002	1.65+002	1.7
33.345	1.783	1.69+002	1.68+002	0.7
35.125	1.777	1.70+002	1.71+002	-0.3
36.892	1.757	1.72+002	1.72+002	-0.2

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 16

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
30.485	3.569	1.63+002	1.63+002	0.2
33.995	3.451	1.69+002	1.69+002	-0.4
37.418	3.396	1.71+002	1.73+002	-0.6
40.787	3.342	1.74+002	1.73+002	0.7
44.141	3.366	1.73+002	1.72+002	0.6
47.552	3.454	1.69+002	1.69+002	-0.3
51.036	3.514	1.66+002	1.65+002	0.2

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1509 17

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
37.990	6.154	1.73+002	1.73+002	-0.2
44.172	6.209	1.71+002	1.72+002	-0.6
50.482	6.412	1.66+002	1.66+002	-0.1
57.076	6.775	1.57+002	1.57+002	0.0
64.060	7.193	1.48+002	1.47+002	0.6
71.552	7.791	1.36+002	1.37+002	-0.1
79.619	8.344	1.27+002	1.27+002	0.1

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 2,70 1620 18

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
37.989	6.156	1.73+002	1.73+002	-0.2
44.170	6.204	1.71+002	1.72+002	-0.5
50.474	6.406	1.66+002	1.66+002	-0.1
57.067	6.780	1.57+002	1.57+002	-0.1
64.053	7.191	1.48+002	1.47+002	0.6
71.547	7.798	1.36+002	1.37+002	-0.2
79.617	8.343	1.27+002	1.27+002	0.1

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25,70 1403 2

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
77.867	0.896	1.29+002	1.29+002	-0.1
78.768	0.906	1.27+002	1.28+002	-0.5
79.675	0.908	1.27+002	1.27+002	0.1
80.588	0.917	1.26+002	1.26+002	-0.0
81.507	0.921	1.25+002	1.25+002	0.2
82.433	0.932	1.24+002	1.24+002	-0.1
83.368	0.938	1.23+002	1.23+002	-0.2

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 25,70 1736 3

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
79.457	1.791	1.27+002	1.27+002	-0.1
81.265	1.826	1.25+002	1.25+002	-0.5
83.100	1.844	1.24+002	1.24+002	0.0
84.959	1.873	1.22+002	1.22+002	0.0
86.840	1.890	1.21+002	1.20+002	0.4
88.750	1.929	1.18+002	1.18+002	-0.2
90.690	1.951	1.17+002	1.17+002	-0.1

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 918 4

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
83.188	3.621	1.23+002	1.23+002	-0.1
86.868	3.739	1.19+002	1.20+002	-0.5
90.647	3.820	1.17+002	1.17+002	0.1
94.518	3.921	1.14+002	1.14+002	0.1
98.473	3.990	1.12+002	1.11+002	0.6
102.522	4.108	1.09+002	1.09+002	-0.1
106.665	4.178	1.07+002	1.07+002	0.1

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 1310 5

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
89.093	6.799	1.18+002	1.18+002	0.0
96.063	7.142	1.13+002	1.13+002	-0.4
103.329	7.391	1.09+002	1.09+002	0.2
110.857	7.665	1.05+002	1.05+002	0.2
118.617	7.854	1.02+002	1.02+002	0.6
126.606	8.124	9.91+001	9.92+001	-0.2
134.815	8.293	9.69+001	9.70+001	-0.1

THERMAL CONDUCTIVITY DATA FOR IRON OSRM MAY 26,70 1655 6

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
101.038	13.395	1.10+002	1.10+002	0.2
114.904	14.338	1.03+002	1.03+002	-0.4
129.569	14.991	9.84+001	9.84+001	-0.0
144.873	15.616	9.46+001	9.48+001	-0.2
160.701	16.039	9.20+001	9.18+001	0.1
177.019	16.597	8.89+001	8.93+001	-0.4
193.813	16.991	8.68+001	8.70+001	-0.3

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 3 1600 19

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
197.194	2.658	8.68+001	8.66+001	0.3
199.867	2.689	8.58+001	8.62+001	-0.5
202.554	2.685	8.60+001	8.59+001	0.1
205.246	2.699	8.56+001	8.56+001	0.0
207.945	2.698	8.56+001	8.53+001	0.3
210.657	2.727	8.47+001	8.50+001	-0.3
213.386	2.731	8.45+001	8.47+001	-0.3

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4 1027 20

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
201.996	5.443	8.64+001	8.60+001	0.5
207.481	5.528	8.51+001	8.54+001	-0.3
213.017	5.542	8.49+001	8.48+001	0.2
218.583	5.590	8.43+001	8.42+001	0.2
224.182	5.608	8.39+001	8.36+001	0.3
229.830	5.688	8.28+001	8.31+001	-0.4
235.533	5.717	8.23+001	8.27+001	-0.5

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 4,70 1600 21

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
209.874	10.393	8.58+001	8.51+001	0.8
220.379	10.617	8.40+001	8.40+001	-0.0
231.041	10.708	8.33+001	8.30+001	0.3
241.829	10.867	8.22+001	8.22+001	0.0
252.742	10.961	8.14+001	8.14+001	0.0
263.813	11.181	7.98+001	8.06+001	-0.9
275.057	11.307	7.88+001	7.97+001	-1.1

Table 5 (continued)

THERMAL CONDUCTIVITY DATA FOR IRON OSRM JUNE 5,70 1405 22

MEAN TEMPERATURE	TEMPERATURE DIFFERENCE	OBSERVED THERMAL CONDUCTIVITY	CALCULATED THERMAL CONDUCTIVITY	PERCENT DEVIATION
277.943	2.862	8.05+001	7.95+001	1.3
280.826	2.906	7.93+001	7.92+001	0.1
283.733	2.907	7.93+001	7.89+001	0.5
286.648	2.925	7.89+001	7.86+001	0.4
289.576	2.930	7.87+001	7.83+001	0.5
292.528	2.973	7.76+001	7.80+001	-0.5
295.506	2.984	7.72+001	7.76+001	-0.5

Table 6. Electrical resistivity deviations for OSRM iron-1265.

MEAN TEMPERATURE	TEMPERATURE RANGE	OBSERVED RESISTANCE	CALCULATED RESISTANCE	PERCENT DEVIATION
5.987	1.880	6.498-005	6.498-005	0.00
8.026	3.569	6.508-005	6.508-005	-0.00
11.644	6.233	6.529-005	6.529-005	0.01
18.184	10.909	6.601-005	6.602-005	-0.02
22.625	3.302	6.671-005	6.669-005	0.02
25.476	6.524	6.749-005	6.749-005	-0.01
31.460	12.982	7.011-005	7.015-005	-0.05
40.774	24.093	7.833-005	7.826-005	0.08
57.851	48.878	1.131-004	1.131-004	-0.02
57.846	48.877	1.131-004	1.131-004	-0.01
80.601	6.418	1.811-004	1.811-004	0.02
85.009	13.104	2.009-004	2.008-004	0.05
94.698	27.377	2.493-004	2.493-004	0.01
111.341	53.268	3.447-004	3.448-004	-0.03
145.990	107.968	5.714-004	5.713-004	0.02
205.265	18.887	9.872-004	9.872-004	0.00
218.661	39.117	1.090-003	1.090-003	0.01
242.106	76.033	1.278-003	1.278-003	0.01
286.680	20.486	1.649-003	1.649-003	0.00
4.422	0.000	6.495-005	6.495-005	-0.00
19.853	0.000	6.616-005	6.616-005	0.01
76.128	0.000	1.628-004	1.628-004	0.00

Table 7. Thermovoltage deviations for OSRM iron-1265

UPPER TEMPERATURE	LOWER TEMPERATURE	OBSERVED THERMOVOLTAGE	CALCULATED THERMOVOLTAGE	DEVIATION
6.880	5.000	-0.08	-0.18	0.10
9.681	6.112	-0.07	0.03	-0.10
14.491	8.258	-0.00	0.00	-0.00
23.154	12.245	1.14	1.05	0.09
24.245	20.943	0.77	0.89	-0.12
28.646	22.122	2.68	2.84	-0.16
37.771	24.789	12.16	12.22	-0.06
52.793	28.700	52.77	52.62	0.15
83.791	34.913	262.39	262.43	-0.04
83.789	34.911	262.37	262.41	-0.03
83.837	77.419	58.70	58.62	0.09
91.666	78.561	128.77	128.73	0.04
108.755	81.377	305.82	305.83	-0.01
138.961	85.693	688.22	688.20	0.02
202.309	94.341	1594.28	1594.28	-0.00
214.752	195.865	299.87	299.93	-0.05
238.391	199.275	613.14	613.13	0.01
280.710	204.678	1148.37	1148.36	0.01
296.998	276.512	281.31	281.33	-0.02

Table 8. Transport properties of OSRM iron-1265

Temp (K)	Thermal Conductivity ($Wm^{-1} K^{-1}$)	Electrical Resistivity (n ohm m)	Lorenz ratio $\times 10^8$ (V^2/K^2)	Thermo-power ($\mu V/K$)
6	38.8	3.867	2.50	-0.06
7	45.3	3.870	2.50	0.02
8	51.8	3.851	2.49	0.04
9	58.2	3.845	2.49	0.04
10	64.7	3.852	2.49	0.04
12	77.4	3.873	2.50	0.08
14	89.7	3.887	2.49	0.15
16	101	3.896	2.47	0.24
18	113	3.905	2.45	0.35
20	123	3.920	2.42	0.46
25	146	3.988	2.33	0.78
30	162	4.098	2.21	1.20
35	171	4.264	2.08	1.75
40	173	4.501	1.95	2.44
45	171	4.836	1.84	3.23
50	167	5.279	1.76	4.09
55	160	5.847	1.70	5.01
60	153	6.542	1.67	5.94
65	145	7.367	1.65	6.88
70	139	8.322	1.65	7.80
75	132	9.379	1.66	8.68
80	127	10.56	1.67	9.52
85	122	11.88	1.70	10.31
90	117	13.27	1.73	11.05
95	114	14.76	1.77	11.74
100	110	16.32	1.80	12.37
110	105	19.69	1.88	13.47
120	101	23.30	1.97	14.37
130	98.3	27.07	2.05	15.10
140	95.8	30.97	2.12	15.67
150	93.8	34.97	2.19	16.10
160	92.0	39.10	2.25	16.41
170	90.3	43.23	2.30	16.63
180	88.9	47.47	2.34	16.76
190	87.5	51.78	2.38	16.82
200	86.2	56.13	2.42	16.81
220	84.0	65.16	2.49	16.64
240	82.3	74.45	2.55	16.31
260	80.8	84.19	2.62	15.83
280	79.3	94.29	2.67	15.23

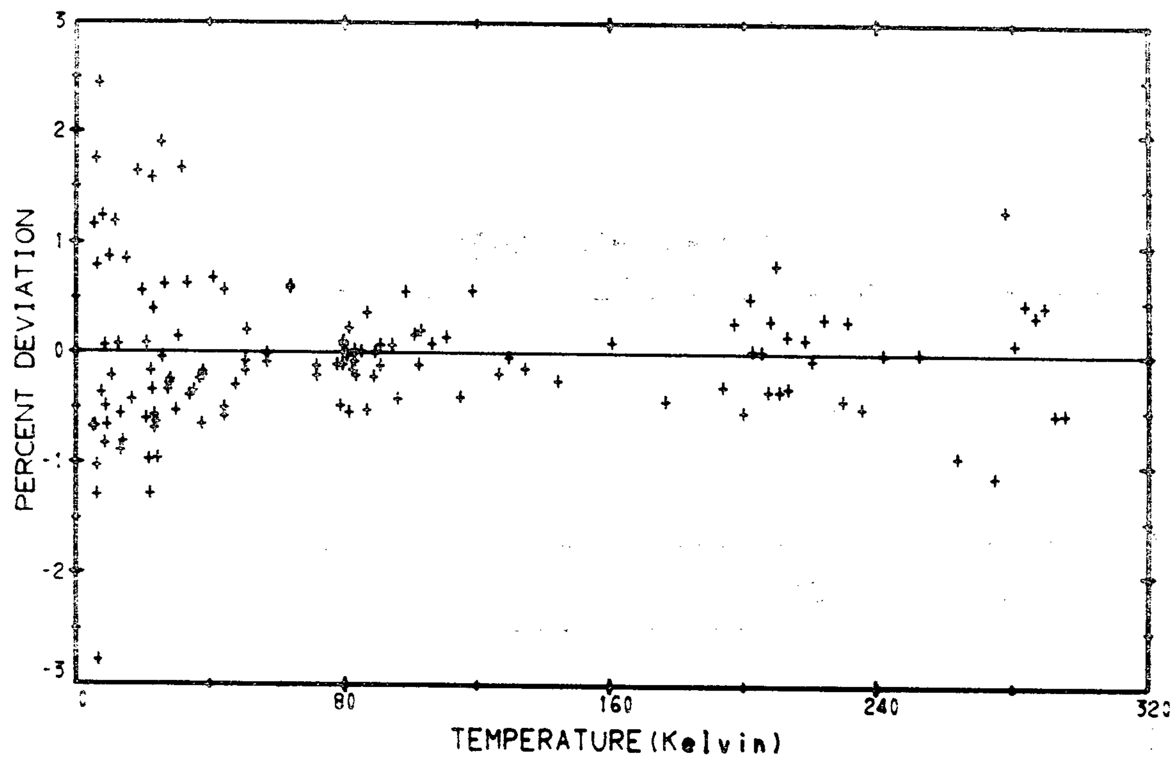

Figure 1. Thermal conductivity deviations for OSRM iron-1265

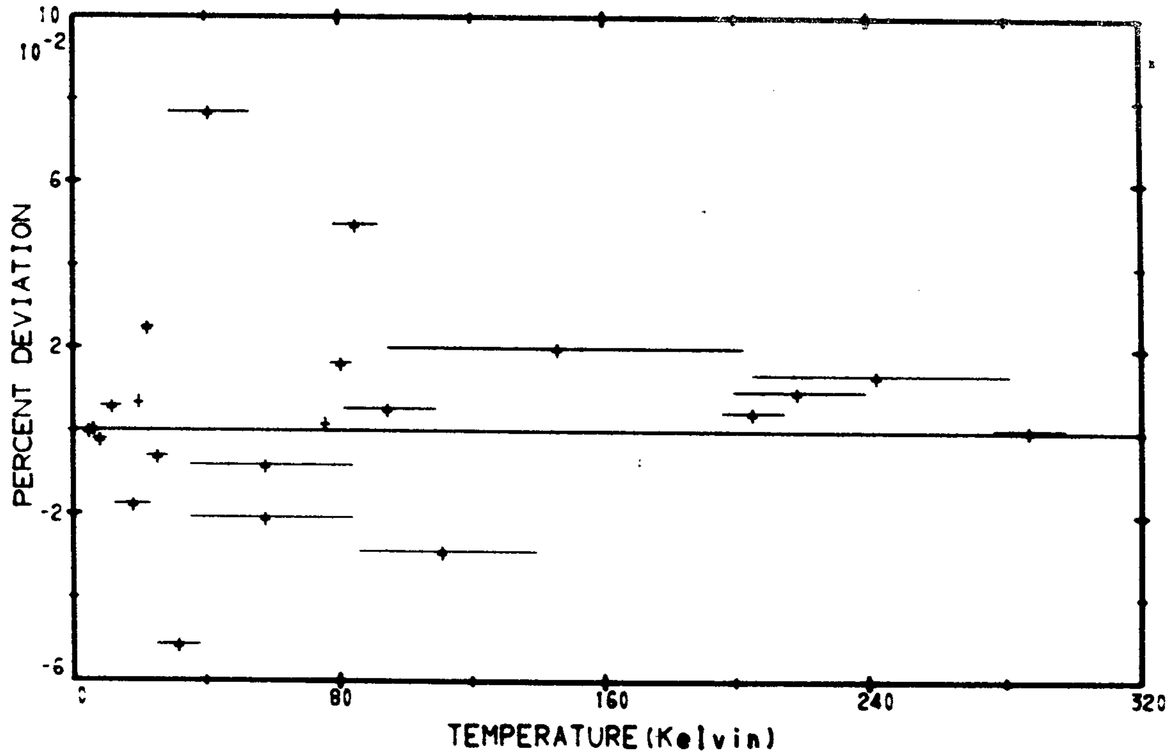

Figure 2. Electrical resistivity deviations for OSRM iron-1265

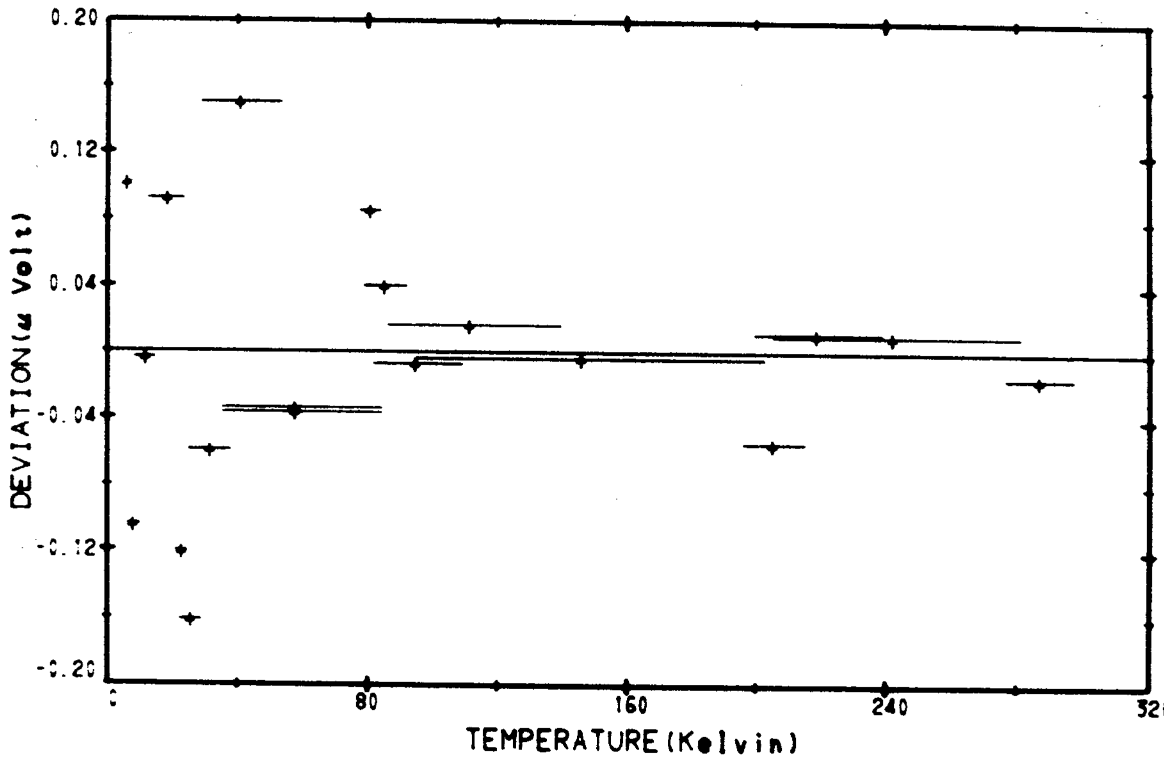

Figure 3. Thermovoltage deviations for OSRM iron-I265

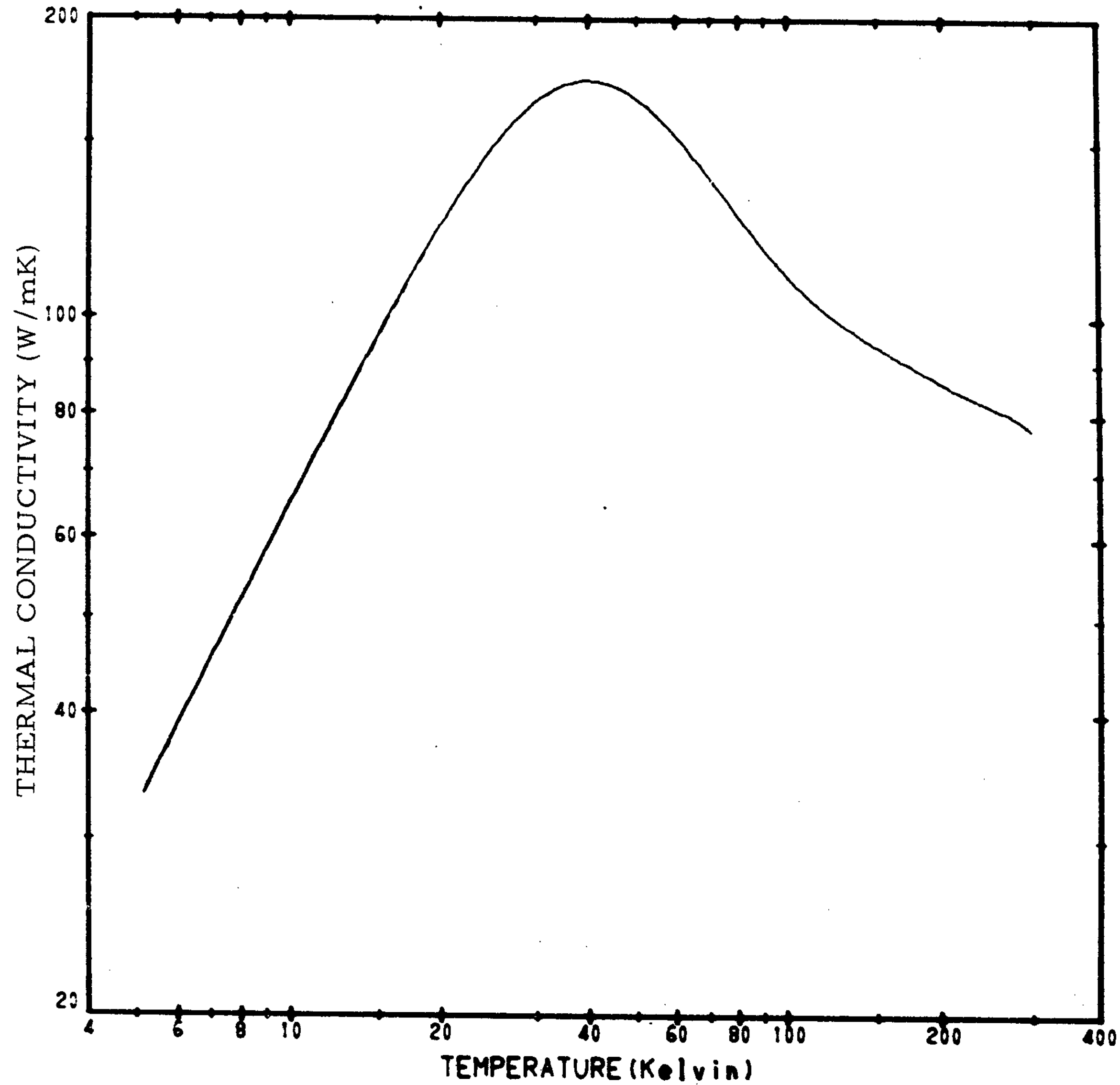

Figure 4. Thermal conductivity of OSRM iron-1265

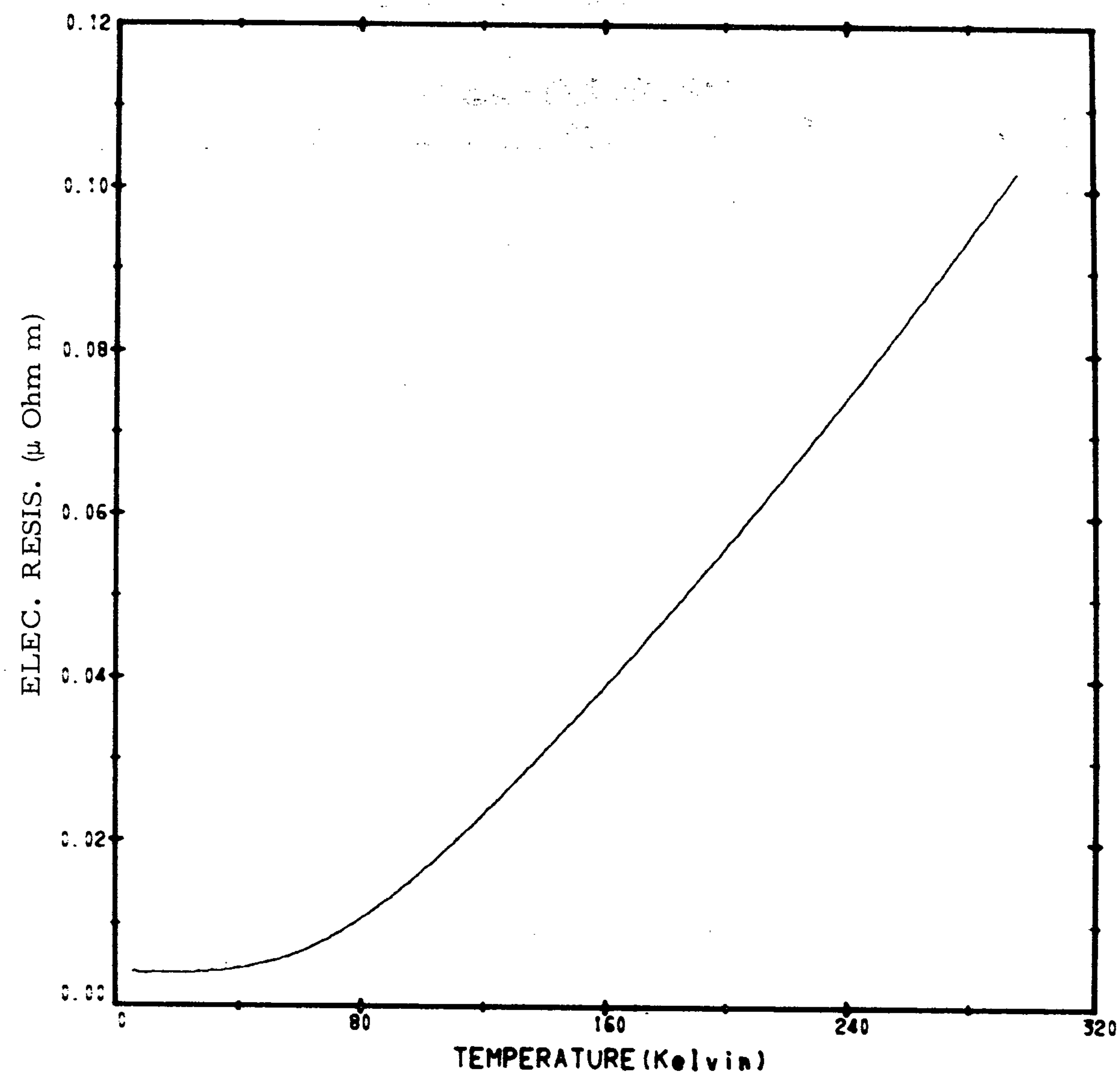

Figure 5. Electrical resistivity of OSRM iron-1265

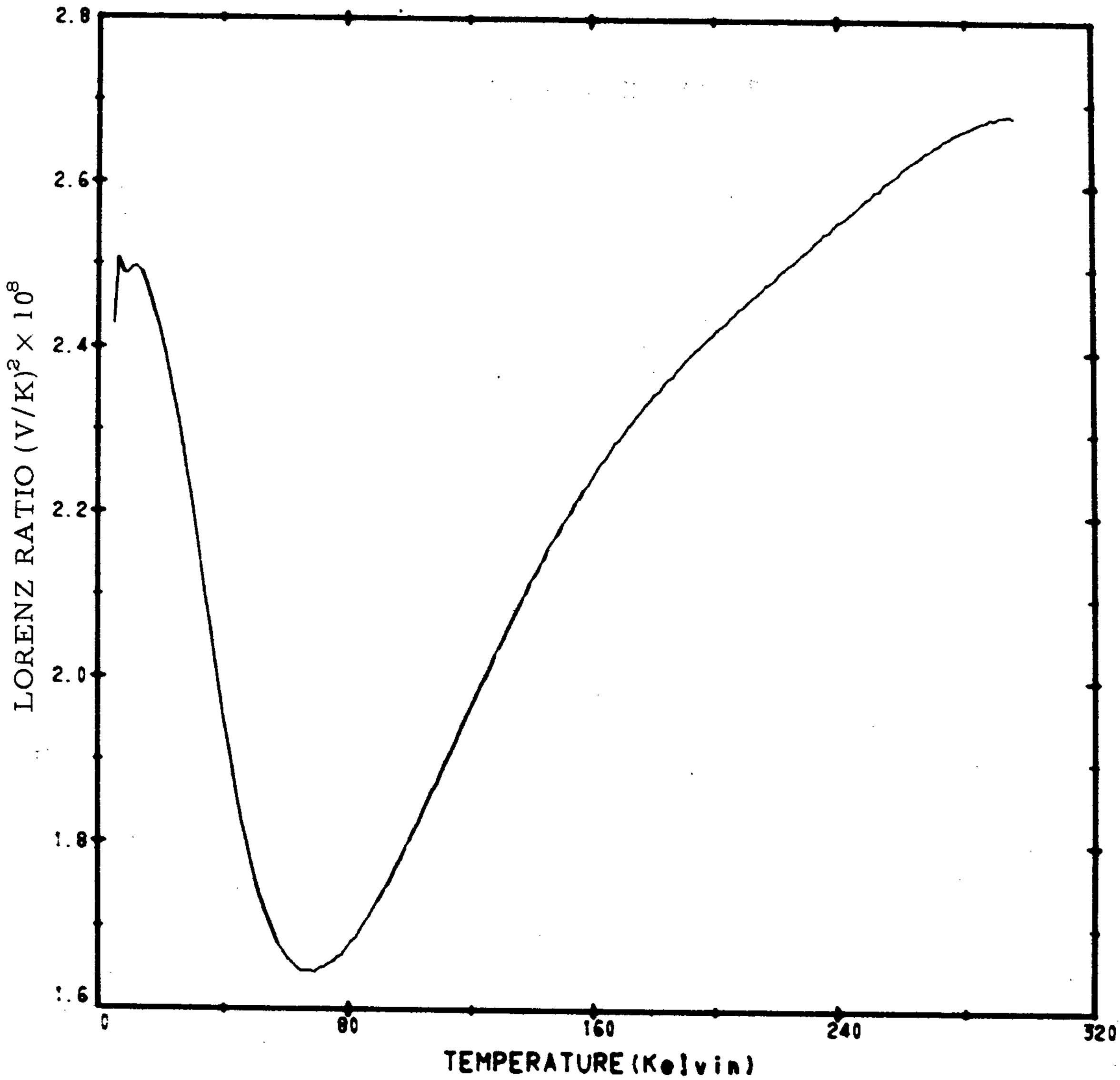

Figure 6. Lorenz ratio of OSRM iron-1265

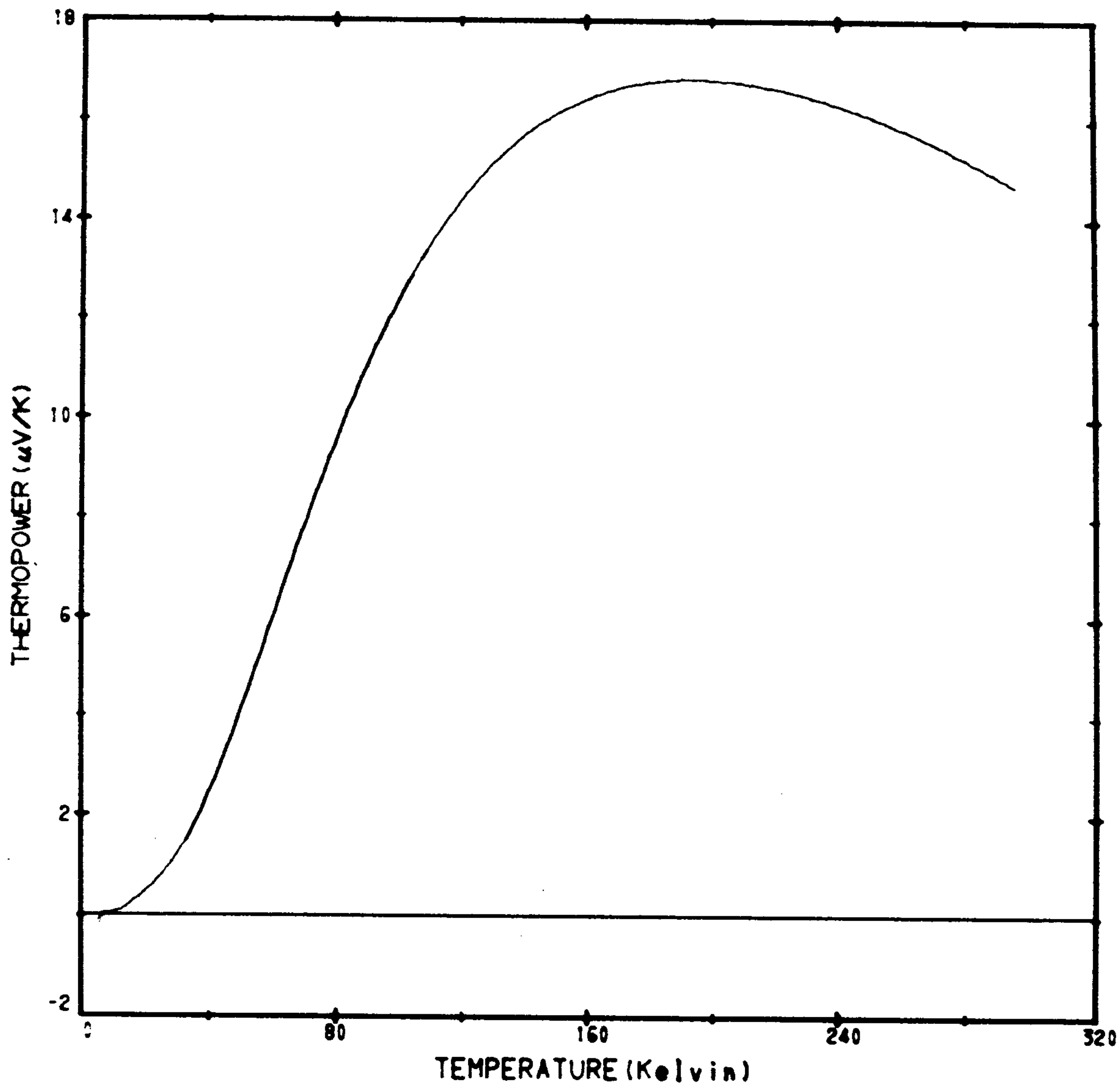

Figure 7. Thermopower of OSRM iron-1265